

## A Simple Constant-Current Neural Stimulator With Accurate Pulse-Amplitude Control

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**Abstract:** A simple constant-current electrocutaneous stimulator for high-impedance loads using low-cost, standard high-voltage components is presented. A voltage-regulator powers an oscillator built across the primary of a transformer whose secondary delivers, after rectification, the high-voltage supply to switched current-mirrors in the driving stage. Since the compliance high-voltage is proportional to the stimulation current, overall power consumption is minimized. By adjusting the regulated voltage, control of the pulsed-current amplitude is achieved. A prototype with readily available components features stimulation currents of amplitude and pulsewidth in the range  $0 \leq I_{\text{skin}} \leq 20\text{mA}$  and  $50\mu\text{s} \leq T_{\text{pulse}} \leq 1\text{ms}$ , respectively. Pulse-repetition spans from 1Hz to 10Hz. Worst-case ripple is 3.7% @  $I_{\text{skin}}=1\text{mA}$ . Measured pulse fall-time is shorter than  $32\mu\text{s}$ . Overall consumption is 4.4W @  $I_{\text{skin}}=20\text{mA}$ . Subject isolation from power line is 4KV.

### I. INTRODUCTION

Electrical stimulators represent a class of medical electronic devices that are useful either therapeutically as prostheses [1-3]. They have been powerful tools to restoring partial functionality to neurologically damaged individuals while providing a medical diagnostic of the nervous system. Stimulation that innervates the muscles can be used in physical therapy to regain some degree of muscular control. Functional Electric-Stimulation (FES) systems are mainly useful in cases dealing with temporary paralysis caused by atrophy of the muscle owing to disuse that considerably reduces its mass. By means of a periodic direct stimulation, the clinician can exercise the damaged muscle, even though normal neuro-stimulation is not available. Additionally, programmed electrical-stimulation can be used to enhance function of paralyzed muscles resulted from neurological injury.

Stimuli parameters vary widely according to the type of muscle stimulation, the number of channels, the type of electrodes and the specified safety-factor. Many commercially available stimulators deliver voltage pulses and require additional features to monitor and set up the current level as it changes with the electrode/skin load-characteristic. Constant-current stimulators are therefore mostly indicated since the charge transferred per stimulus is constant regardless the load impedance. On the current-pump stimulator reported by Poletto et al. [4], the voltage-to-current (V/I) converter requires op-amps with a particular combination of high-voltage tolerance and large slew-rates while demanding special care for frequency compensation and over-voltage/current protection. Its output stage uses five power-supply modules so that a power-up management circuit is needed to establish the appropriate turn-on sequence of these supplies. On the approach proposed by Kaczmarek et al. [5], the V/I conversion requires a fixed-value high-voltage supply, regardless the

amplitude of the stimulation current. In this case, additional circuitry would be necessary to minimize safety hazardous and stand-by power consumption.

This work describes an alternative and simple constant-current stimulator employing only conventional high-voltage components while featuring good controllability of stimulation parameters such as amplitude, duration and frequency of the pulsed-current. Its small number of components makes it attractive for low-cost applications. Basically, a voltage-regulator powers an oscillator built around the primary of an elevator transformer whose secondary delivers, after rectification, the necessary compliance voltage to a switched V/I converter in the driving stage. Furthermore, subject isolation from the power line is naturally achieved. Accurate amplitude-control of the load current is performed in the voltage-regulator, whereas pulsewidth is controlled by an optically-coupled monostable. In contrast with [5], the high-voltage supplied to the V/I converter has its value proportional to the stimulation current, reducing thus power consumption and improving safety protection. Although originally devised to stimulate muscles through the skin, the proposed topology can be extended to other ranges of neural stimulators.

The paper outline is as follows. Section II describes the proposed stimulator topology and schematic, whose design is discussed in Section III. Experimental results are presented in Section IV. Concluding remarks are summarized in Section V.

### II. DESCRIPTION OF THE NEURAL STIMULATOR

The block diagram of the proposed neurostimulator is displayed in Figure 1. It consists of a pair of transformers followed by full-bridge rectifiers, an adjustable voltage-regulator, a multivibrator, a photocoupler, a switching circuit and a V/I converter in the driving stage. The load represents both resistive and reactive components of the electrode/skin interface as well as the bulk tissue resistance.

Specified intervals for the amplitude and pulsewidth of the stimulation current are  $0 \leq I_{\text{skin}} \leq 20\text{mA}$  and  $50\mu\text{s} \leq T_{\text{pulse}} \leq 1\text{ms}$ , respectively. The ripple associated with  $I_{\text{skin}}$  is limited to 6%. Pulse-repetition ranges from 1Hz to 10Hz.

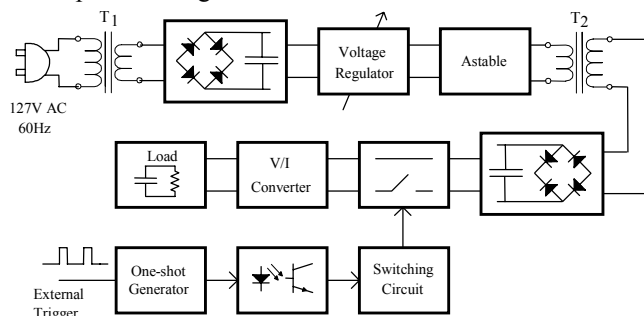


Figure 1. Block diagram of the neurostimulator

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The circuit operation is now briefly described. Line transformer  $T_1$  steps the 60Hz mains-voltage down to  $30V_{AC}$ . Following a four-diode bridge and a bulk-capacitor filter, the rectified voltage is input to a regulator circuit, whose output is adjustable within the interval 0-12V and sets the supply voltage to the astable. Since such a circuit is loaded by the primary of the elevator-transformer  $T_2$ , the oscillation across the secondary attains high-voltage amplitudes and provides the necessary compliance voltage to generate the desired stimulation currents. As function of the regulated voltage, the peak-amplitude at the secondary of  $T_2$  varies from 0 to 220V. After a second full-bridge rectifier, a high-voltage supply is available to a switched V/I converter built upon cascode current mirrors that delivers to the load a constant-amplitude pulsed-current. Pulse duration is externally set up by a monostable and triggered by a TTL-level signal. The resulting one-shot pulse is delivered to a photocoupler that drives a switching circuit made up of discrete transistors.

For explanatory reasons, the neurostimulator schematic is split into three main elements: the oscillator, the output V/I converter and the switching circuit. These parts are discussed below in more details.

#### A. Controlled-Amplitude Oscillator

The oscillator schematic is illustrated in Figure 2.  $T_1$  is a transformer with a ratio of windings  $N_1=1:6$  and lowers the power-line voltage from  $127V_{AC}$  rms to  $30V_{peak}$ . Following a full-bridge rectifier with diodes  $D_1$ - $D_4$  (1N4007) and filter-capacitor  $C_1$ , the rectified voltage is input to a voltage-regulator (LM317T), whose output  $V_R \approx 1.25(1+R_2/R_1)[V]$  is tunable within 1.25V-30V. Ultimately, the magnitude of the stimulation current is proportional to the regulated voltage, which can be adjusted by potentiometer  $R_2$  in the present prototype. Nevertheless, advanced versions may feature a programmable adjustment, by means of a D/A output of a microcontroller, for instance. Diodes  $D_5$ - $D_6$  (1N4007) produce the voltage drop that ensures 0V as the minimum dc-voltage  $V_R$  supplied to a multivibrator astable, which comprises bipolar transistors  $Q_1$ - $Q_2$  (TIP41C), base resistors  $R_3$ - $R_4$  and collector-coupling capacitors  $C_4$ - $C_5$ . Since oscillation is developed across the center-tapped primary of transformer  $T_2$ , which has a ratio of windings  $N_2=1:15$ , a high-voltage oscillation appears at its secondary. Supply-voltages  $V_{DDO}^+$  and  $V_{DDO}^-$  are available after a dc-conversion by the bridge  $D_{10}$ - $D_{13}$  (1N4007) and  $C_7$ .

#### B. Voltage-to-Current Converter

Figure 3 shows the schematic of the driving stage, built around a self-biased current-mirror formed by MOS transistors  $M_1$ - $M_4$ . The standard cascode configuration was chosen by its simplicity while providing a high dynamic output-resistance [6]. All transistors are N-channel devices (MPT2N60).  $R_E$  and  $C_E$  are the reactive components of the electrode/skin interface and  $R_{skin}$  is the tissue resistance. Fixing  $R_5$  and denoting  $V_{DDO}=V_{DDO}^+-V_{DDO}^-$ , it comes out  $I_{skin}=(V_{DDO}-V_{GS1}-V_{GS3})/R_5$ .  $V_{DDO}$  determines then the current through the skin, which is independent of the load characteristic, at good approximation. Adjusting  $I_{skin}$  by means of  $R_2$  in the voltage-regulator compensates for the poor matching between discrete transistors in the current mirror. Upon assertion of phase  $\Phi_1$ ,  $M_5$  switches

on the current mirror, so that a pulsed current is delivered by the stage.

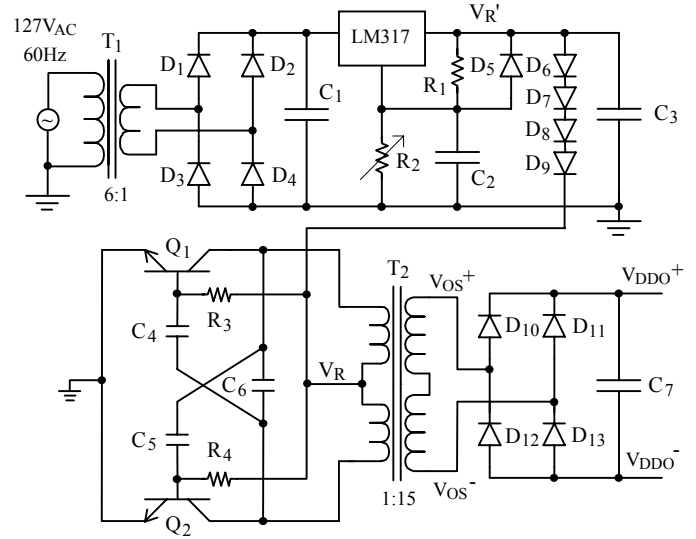


Figure 2. Oscillator schematic

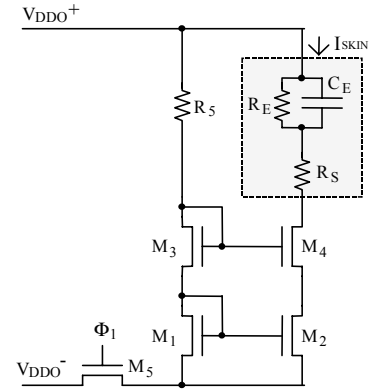


Figure 3. Schematic of the driving stage

#### C. Timing and Switching Circuit

Figure 4 shows the timing and switching circuit, comprising a photocoupler (4N25), which electrically isolates the stimulator from the external circuitry that imposes the pulse duration, and a push-pull driver. On the present prototype, the pulse duration of the load current is imposed by a monostable formed by  $Q_3$ - $Q_4$  (BC547),  $Q_5$  (TIP41),  $Q_6$  (TIP42),  $R_7$ - $R_{11}$  and  $C_8$ - $C_9$ , and triggered by a TTL-level signal  $V_{TR}$ . The one-shot pulse is then input to the optocoupler. High-voltage control phase  $\Phi_1$  is available at the push-pull (TIP41, TIP42) output.

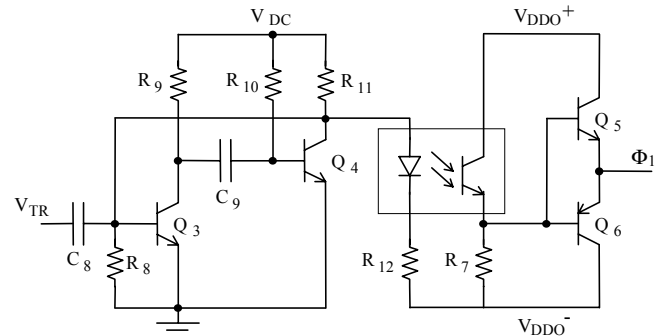


Figure 4. One-shot generator and switching circuit

### III. CIRCUIT DESIGN

Considering the use of electrodes with small surface areas, a maximum value of  $10\text{K}\Omega$  was assumed for the highly nonlinear resistance  $R_{\text{skin}}$  that mimics the electrode/skin interface and the bulk resistance [4,7]. Adopting  $R_5=10\text{K}\Omega$  and accounting for voltage drops  $V_{\text{DSAT2}}$ ,  $V_{\text{DSAT4}}$  and  $V_{\text{DS5}}$  in the driving stage, a compliance voltage  $V_{\text{DDO}}=210\text{V}$  assures proper current mirroring at maximum  $20\text{mA}$ -load current. As a result, the amplitude of the oscillation to be developed across the secondary of  $T_2$  should reach  $420\text{V}_{\text{pp}}$ , which imposes  $1\text{V} \leq V_R \leq 14\text{V}$  as the operation range to the voltage-regulator. It is worth noticing that  $V_R=0$  entails  $I_{\text{skin}}=0$ .

The design requirements on sizing filter-capacitor  $C_7$  are twofold: i) the minimum energy per a pulsed stimulus and ii) the highest allowed ripple on  $I_{\text{skin}}$ . Neglecting the consumption dissipated by the current-mirror transistors, the energy to be delivered by  $C_7$  is  $E_{\text{tot}} \approx 2R_{\text{skin}}I_{\text{skin}}^2T_{\text{pulse}} + E_{\text{opt}}$ , where  $E_{\text{opt}}$  is the optocoupler component. Straightforward manipulation leads to  $C_7 \geq 2(2+\eta)T_{\text{pulse}}/R_{\text{skin}}$ , where  $\eta=I_{\text{opto}}/I_{\text{skin}}$  and  $I_{\text{opto}}$  is the current delivered by the optocoupler.  $C_7$  should thus be sized in accordance with the largest pulsewidth and smallest amplitude of  $I_{\text{skin}}$ . A preliminary characterization of  $I_{\text{opto}}$  as function of the stimulation current is displayed in Figure 5. Taking  $T_{\text{pulse}}=1\text{ms}$  and  $I_{\text{skin}}=1\text{mA}$ , it comes out  $C_7 \geq 1.33\mu\text{F}$  for  $I_{\text{opto}}=4.6\text{mA}$ .

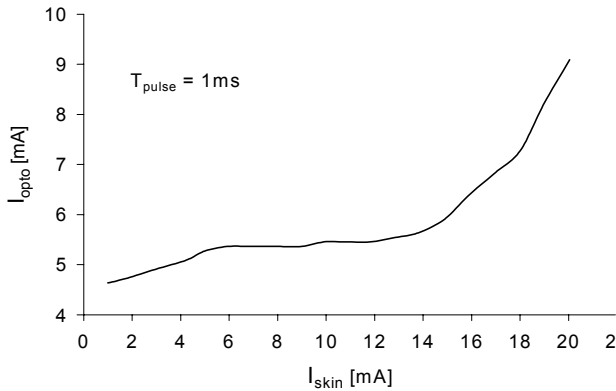


Figure 5. Dependence of  $I_{\text{opto}}$  on the stimulation current

The ripple factor is given by  $[1-\exp(-T_{\text{pulse}}/\tau)]$ , where  $\tau=R_L C_7$  and  $R_L \approx R_{\text{skin}}/R_5/R_{\text{opto}}$  is the filter resistive-load.  $R_{\text{opto}}$  denotes the dc-resistance  $V_{\text{DDO}}/I_{\text{opto}}$  of the optocoupler branch. Based on the measurements presented in Figure 5, one has  $1.95\text{K}\Omega \leq R_L \leq 4.1\text{K}\Omega$  for the given range of  $V_{\text{DDO}}$  and  $I_{\text{skin}}$ . Adopting  $C_7=8.8\mu\text{F}$ , the calculated ripple for worst-case  $1\text{ms}$ -pulsewidth is  $5.66\%$  @  $I_{\text{skin}}=1\text{mA}$  and  $2.73\%$  @  $I_{\text{skin}}=20\text{mA}$ . Larger values of  $C_7$  would decrease the ripple, at expense of higher overall consumption, as  $V_R$  should be increased.

Supposing that the astable generates a square waveform and approximating the analysis to the case of a purely resistive-load at the collector of  $Q_1$ - $Q_2$ , the oscillation period is  $T_a \approx 2R_3 C_X \ln[(V_R - V_{\text{BE}})/(2V_R + V_{\text{BE}} - V_{\text{CEsat}})]$ , where  $C_X$  represents the series association of  $C_4$  and  $0.5C_6$ . Choosing  $R_3=R_4=10\text{K}\Omega$ ,  $C_4=C_5=0.47\mu\text{F}$  and  $C_6=2.2\mu\text{F}$ , the oscillation-frequency interval is  $170\text{Hz} \leq f_a \leq 199\text{Hz}$ . Setting such relatively low frequencies aims to reduce the oscillator power consumption, and consequently, the current supplied by the voltage-regulator, while still complying with the specified ripple on the stimulation current.

Pulsewidth spans from  $50\mu\text{s}$  to  $1\text{ms}$  and can be adjusted by potentiometer  $R_9$  in the monostable. Other components are  $R_7=1\text{K}\Omega$ ,  $R_8=R_{10}=10\text{K}\Omega$ ,  $R_{11}=1\text{K}\Omega$  and  $C_8=C_9=1\mu\text{F}$ .

### IV. EXPERIMENTAL RESULTS

A wire-wrapped prototype of the neurostimulator was implemented. Heat sinks were properly attached to the voltage-regulator and the optocoupler. Both transformers  $T_1$  ( $15\text{VA}$ ) and  $T_2$  ( $3\text{VA}$ ) provide a minimum  $4\text{KV}$ -isolation. All resistors are  $1/4\text{W}$ -carbon with  $5\%$ -tolerance.

To appraise the stimulator limits without the restriction imposed by subject pain-threshold, a  $10\text{K}\Omega$ -load resistor  $R_{\text{skin}}$  was initially fixed. The measured transfer function of the circuit, defined as the amplitude of the load current against the regulated voltage, is shown in Figure 6, for stimulation rates of  $1\text{Hz}$  and  $10\text{Hz}$ . At maximum-current condition, the waveform of the oscillation at the secondary of  $T_2$  is shown in Figure 7. Amplitude and frequency are  $438\text{V}_{\text{pp}}$  and  $204\text{Hz}$ , respectively.

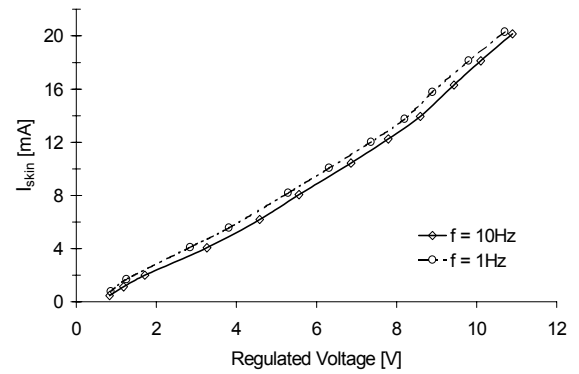


Figure 6. Measured amplitude of  $I_{\text{skin}}$  as function of regulated voltage

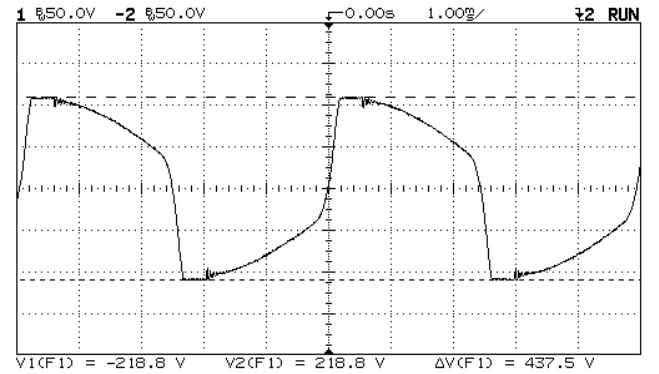


Figure 7. Oscillation at  $T_2$  secondary at condition of  $I_{\text{skin}}=20\text{mA}$

A volunteer subject was solicited after the ethical approval for the project was granted. Prior to stimulation, the skin of the subject's wrist was abraded and an electrolyte gel applied to improve contact with the electrode leads. Tests were performed at different stimulation ratings. The waveforms of the voltage across  $R_5$  (a) and skin electrodes (b) at  $I_{\text{skin}}=20\text{mA}$  are shown in Figures 8 and 9, for  $T_{\text{pulse}}=50\mu\text{s}$  and  $T_{\text{pulse}}=1\text{ms}$ , respectively. Measured pulse transitions shorter than  $32\mu\text{s}$  make the circuit suitable to relatively high stimulation rates.

The relative peak-to-peak ripple on the pulsed current as function of the amplitude is shown in Figure 10, for  $C_7=8.8\mu\text{F}$  and pulses  $1\text{ms}$ -long. A maximum variation of  $2.5\%$  was found within the interval  $4\text{mA} \leq I_{\text{skin}} \leq 20\text{mA}$ , which is slightly lower

than the calculated values. As expected, ripple increases at lower  $I_{skin}$  values as  $\tau=R_L C_7$  follows the reduction of  $R_{opto}$ . The stimulator consumption is 4.4W @ $I_{skin}=20mA$ . A summary of measured parameters of the stimulator is listed in Table 1.

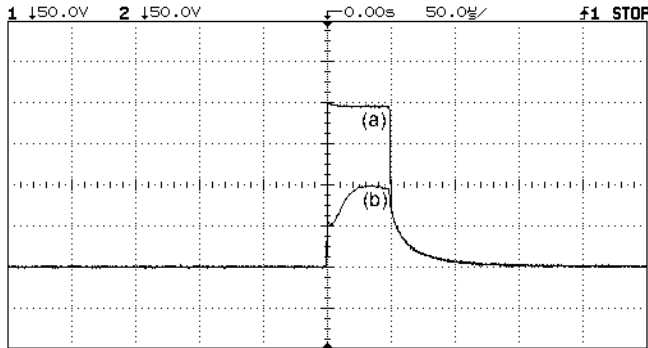


Figure 8. Voltage across skin electrodes at  $I_{skin}=20mA$  and  $T_{pulse}=50\mu s$

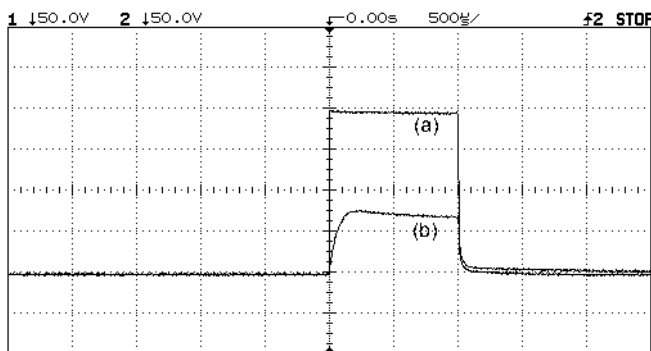


Figure 9. Voltage across skin electrodes at  $I_{skin}=20mA$  and  $T_{pulse}=1ms$

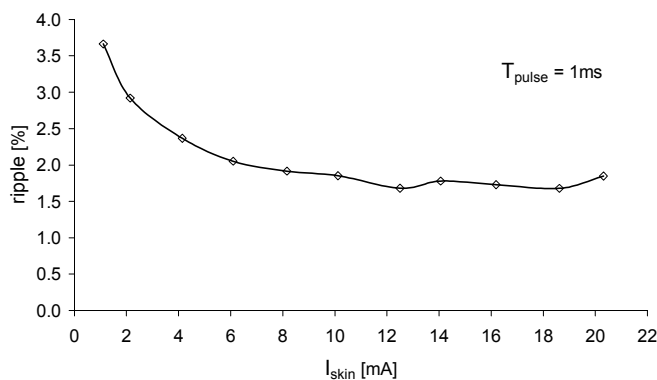


Figure 10. Measured ripple on stimulation-current as function of amplitude

## V. CONCLUSION

A constant-current neurostimulator based upon standard high-voltage components was presented. It basically comprises a voltage-regulator that powers an oscillator built around the primary of a transformer. The secondary supplies, after rectification, the high-voltage to a switched current-mirror in the output driving stage. Since the compliance high-voltage is proportional to the stimulation current, consumption is reduced, which is attractive for battery-operated applications. The current amplitude is adjusted by the regulated voltage,

whereas the pulse duration is controlled by an optically-coupled monostable circuit.

A prototype employing readily available components exhibits stimulation currents of amplitude and pulsewidth in the interval  $0 \leq I_{skin} \leq 20mA$  and  $50\mu s \leq T_{pulse} \leq 1ms$ , respectively. Stimulation rate is from 1Hz to 10Hz. The measured ripple is 3.7% @ $I_{skin}=1mA$  and 1.9% @ $I_{skin}=20mA$ . Total power consumption is 4.4W @ $I_{skin}=20mA$ . Subject isolation from power line is 4KV.

Although the circuit is devised to electrocutaneous stimulation of muscles and designed for a maximum skin-resistance of  $10K\Omega$ , the proposed topology can be applied to other ranges of stimulators. Its small number of components and low consumption make it valuable for low-cost and remote applications. The use of components with higher voltage specifications can accommodate larger values of stimulation current and skin resistance.

TABLE 1  
NEUROSTIMULATOR MEASURED CHARACTERISTICS

	Min	Max
Output Current (mA)	0	20
Pulse Duration ( $\mu s$ )	50	1000
Fall Time ( $\mu s$ )	-	32
Ripple (%)	1.9	3.7
Stimulation Rate (Hz)	1	10
Consumption (W)	2.7	4.4

## ACKNOWLEDGMENTS

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## REFERENCES

- [1] *Medical Instrumentation: Application and Design*, edited by Webster, J. G., 3<sup>rd</sup> Edition, John Wiley & Sons, 1998.
- [2] Peckham, P. H. – “Functional Electrical Simulation”, *Encyclopedia of Medical Devices and Instrumentation*, edited by Webster, J. G., pp. 1331-1352, John Wiley & Sons, 1988.
- [3] Gudnason, G., Bruun, E. & Haugland, M. – “An Implantable Mixed Analog/Digital Neural Stimulator Circuit”, *Proc. of ISCAS99*, Orlando, USA, pp. V.375 – V.378, 1999.
- [4] Poletto, C. & Van Doren, C. – “A High Voltage, Constant Current Stimulator for Electrocutaneous Stimulation Through Small Electrodes”, *IEEE Trans. on Biomedical Engineering*, Vol. 46, No. 8, Aug. 1999.
- [5] Kaczmarek, K., Kramer, K., Webster, J. & Radwin, R. – “A 16-Channel 8-Parameter Waveform Electrotactile Stimulation System”, *IEEE Trans. on Biomedical Engineering*, Vol. 38, No. 10, Oct. 1991.
- [6] Johns, D. & Martin, K. – “*Analog Integrated Circuit Design*”, John Wiley & Sons, 1997.
- [7] “Neurostimulator Characteristics”, Internal Report #27/00, Neurotec.